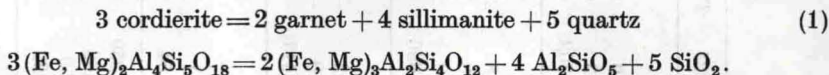Table 1. *Compositions of coexisting garnet, cordierite, and biotite from the Opinicon Lake region*

	H-70	H-29	H-66	69-117	69-38	69-77	69-6	69-29	D28	D56	D87	R114	R124	D102
Cordierite														
MgO	2.11	7.11	6.80	7.17	8.03	9.06	9.94	10.35	9.7	7.7	4.4	6.6	8.9	8.1
FeO	3.24	8.28	5.67	9.75	8.41	6.80	5.42	4.68	5.7	6.0	5.6	7.9	6.9	6.4
$Fe/Fe+Mg$	0.454	0.367	0.319	0.433	0.370	0.303	0.233	0.202	0.248	0.304	0.417	0.502	0.303	0.309
Garnet														
FeO	27.66	28.76	30.87	31.5	30.6	29.3	27.9	26.8	25.9	282	30.9	30.6	27.8	29.3
MgO	5.67	6.70	7.10	6.57	7.25	8.25	9.22	9.90	8.2	6.0	5.0	5.4	6.8	7.3
CaO	1.45	150	1.89	1.58	1.57	1.57	1.54	1.53	2.0	1.7	1.6	2.3	1.9	1.8
$Fe/Fe+Mg$	0.732	0.652	0.704	0.772	0.748	0.713	0.680	0.654	0.638	0.725	0.776	0.761	0.696	0.692
Biotite														
FeO	21.99	18.47	18.28	19.8	21.5	21.9	20.0	19.2	14.2	15.2	18.6	19.2	15.3	—
MgO	8.40	9.70	8.70	10.33	9.57	9.25	10.24	10.55	14.0	11.7	10.3	10.0	12.0	—
$Fe/Fe+Mg$	0.568	0.517	0.540	0.51	0.55	0.57	0.52	0.50	0.363	0.422	0.503	0.519	0.417	—
Bulk rock														
FeO	7.42	6.67	6.67	6.25	6.34	6.87	6.61	6.08	7.8	6.4	9.6	8.2	8.7	5.9
MgO	3.35	3.40	3.15	3.23	2.91	2.91	3.43	3.41	3.7	3.0	3.7	3.4	4.1	2.6
$Fe/Fe+Mg$	0.554	0.523	0.543	0.52	0.59	0.56	0.56	0.53	0.54	0.54	0.59	0.575	0.54	0.56
K	3.29	3.56	3.79	3.90	4.44	5.20	6.11	6.57	5.344	6.036	4.843	4.736	5.259	5.03
$\ln K$	1.19	1.27	1.33	1.36	1.46	1.65	1.81	1.88	1.67	1.80	1.58	1.56	1.66	1.62
T (°A)	870	885	895	900	925	955	990	1005	960	989	942	940	959	950
P (Kbars)	5.76	6.04	6.04	5.68	6.16	6.19	6.46	6.69	6.37	6.37	6.16	5.85	6.22	6.22

Analyses H-70, H-29, H-66 from Wynne-Edwards and Hay (1963); analyses D28, D56, D87, R114, R124, R102 from Reinhardt (1968).

and cordierite are in a reaction relation experimentally realized by Richardson (1968) and by Hirschberg and Winkler (1968), namely

$$3 \text{ cordierite} = 2 \text{ garnet} + 4 \text{ sillimanite} + 5 \text{ quartz} \tag{1}$$

$$3 (\text{Fe, Mg})_2\text{Al}_4\text{Si}_5\text{O}_{18} = 2 (\text{Fe, Mg})_3\text{Al}_2\text{Si}_4\text{O}_{12} + 4 \text{ Al}_2\text{SiO}_5 + 5 \text{ SiO}_2.$$
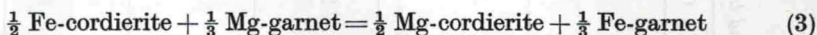
If the rocks have equilibrated, and all phases in Eq. (1) are present and stoichiometric, the presence of other iron and/or magnesium bearing minerals, such as biotite or hypersthene, does not change the equilibrium constant defined by (1), but alters the amounts of garnet and cordierite to permit appearance of minerals with $\text{Fe}/\text{Fe} + \text{Mg}$ ratios controlled by equations analogous to (1), for example

$$4 \text{ biotite} + 3 \text{ cordierite} = 6 \text{ garnet} + 4 \text{ K-feldspar} + 4 \text{ H}_2\text{O}. \tag{2}$$
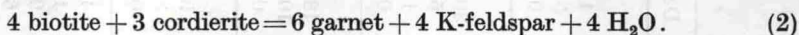
Since Al_2O_3 and SiO_2 are present in excess of the amounts needed to form the iron and iron magnesium silicates in Eq. (1), it follows that variation in $\text{Al}/\text{Fe} + \text{Mg}$ and $\text{Si}/\text{Fe} + \text{Mg}$ ratios do not affect Eq. (1) unless they result in the disappearance of one of the phases. These considerations suggest Eq. (1) as a possible geothermometer, assuming that (a) oxygen fugacity is low enough to prevent oxidation of significant amounts of iron in the garnet and cordierite, (b) cordierite is anhydrous (Schreyer and Yoder 1954), making the reaction independent of water fugacity, (c) cordierite and garnet contain no contaminants replacing significant amounts of iron and magnesium. Whole rock compositions (Wynne-Edwards and Hay, 1963; Reinhardt, 1968; Currie and Ermanovics, in press) show that the contents of the most probably contaminants, Ca and Mn, are notably low in garnet-cordierite gneisses.

Thermodynamic Considerations

The operation of the garnet-cordierite geothermometer may be displayed as follows. Consider the exchange reaction

$$\tfrac{1}{2} \text{ Fe-cordierite} + \tfrac{1}{3} \text{ Mg-garnet} = \tfrac{1}{2} \text{ Mg-cordierite} + \tfrac{1}{3} \text{ Fe-garnet} \tag{3}$$

The theory of such reactions has been treated by Kretz (1961) and others, assuming that each mineral forms an ideal solution of iron and magnesium end members. The cell volumes of both garnet and cordierite are linearly dependent on the mol fraction of the end members (Iiyama, 1956; Rickwood, 1968) which is a necessary but not sufficient condition for ideality. We shall assume ideality, and show below that the rection experimentally shows almost ideal behaviour.

For given (P, T) conditions, reaction (3) will reach an equilibrium described by the equilibrium constant K. The change in Gibbs free energy associated with the reaction may be written

$$\begin{aligned} dF &= - R T \ln K = - R T \ln(X_\text{m}^\text{c}/1 - X_\text{m}^\text{c}) \, (X_\text{f}^\text{g}/1 - X_\text{f}^\text{g}) \\ &= \tfrac{1}{2} F_\text{m}^\text{c} + \tfrac{1}{3} F_\text{f}^\text{g} - \tfrac{1}{2} F_\text{f}^\text{c} - \tfrac{1}{3} F_\text{m}^\text{g} \end{aligned} \tag{4}$$

where F is the Gibbs free energy, T the absolute temperature, R the gas constant, X_j^i the mol fraction of component j in phase i, and $\text{m} - \text{Mg}$, $\text{f} - \text{Fe}$, $\text{g} - \text{garnet}$, $\text{c} - \text{cordierite}$. The volume change in this reaction is negligible (see p. 4), hence K is not explicitly dependent on pressure.